PG 1258+593 and its common proper motion magnetic white dwarf counterpart

J. Girven[1], B. T. Gänsicke[1], B. Külebi[2], D. Steeghs[1], S. Jordan[2], T.R. Marsh[1], D. Koester[3]

[1] *Department of Physics, University of Warwick, Coventry CV4 7AL, UK*
[2] *Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität Heidelberg, Mönchhofstrasse 12-14, D-69120 Heidelberg, Germany*
[3] *Institut für Theoretische Physik und Astrophysik, University of Kiel, 24098 Kiel, Germany*

Started 2009

ABSTRACT

We identify SDSS J130033.48+590407.0 as a common proper motion companion to the well-studied DA white dwarf PG 1258+593 (GD322). The system lies at a distance of 68 ± 3 pc, where the angular separation of $16.1\pm0.1''$ corresponds to a minimum binary separation of 1091 ± 7 AU. SDSS J1300+5904 is a cool ($T_{\rm eff} = 6300 \pm 300$K) magnetic white dwarf ($B \simeq 6$ MG). PG 1258+593 is a hydrogen-rich (DA) white dwarf with $T_{\rm eff} = 14790\pm77$ K and $\log g = 7.87\pm0.02$. Using the white dwarf mass–radius relation implies the masses of SDSS J1300+5904 and PG 1258+593 are $0.54 \pm 0.06\,{\rm M_\odot}$ and $0.54 \pm 0.01\,{\rm M_\odot}$, respectively, and therefore a cooling age difference of 1.67 ± 0.05 Gyr. Adopting main-sequence life times from stellar models, we derive an upper limit of $2.2\,{\rm M_\odot}$ for the mass of the progenitor of PG 1258+593. A plausible range of initial masses is 1.4–$1.8\,{\rm M_\odot}$ for PG 1258+593 and 2–$3\,{\rm M_\odot}$ for SDSS J1300+5904. Our analysis shows that white dwarf common proper motion binaries can potentially constrain the white dwarf initial-final mass relation and the formation mechanism for magnetic white dwarfs. The magnetic field of SDSS J1300+5904 is consistent with an Ap progenitor star. A common envelope origin of the system cannot be excluded, but requires a triple system as progenitor.

Key words: Stars: binaries: white dwarf, magnetic white dwarf – common proper motion pair

1 INTRODUCTION

White dwarfs (WDs) are the end point for the large majority of stars. It has been shown that a significant number, possibly $\sim 10-15\%$, of all WDs may be magnetic with fields $\gtrsim 1$ MG (Liebert et al. 2003; Wickramasinghe & Ferrario 2005). The Sloan Digital Sky Survey (SDSS; York et al. 2000) has been a rich source for finding new magnetic WDs (MWDs) (Gänsicke et al. 2002; Schmidt et al. 2003; Vanlandingham et al. 2005, and Külebi et al. 2009), bringing the number of known MWDs to > 200. However, the formation mechanism for MWDs is still under debate, with the two favoured progenitors being either magnetic Ap/Bp stars (Moss 1989) or close binaries that evolved, and potentially merged, through a common envelope (Tout & Pringle 1992).

In the Ap/Bp scenario, the MWDs field is a relic of the large-scale magnetic fields of their intermediate mass progenitor stars. These in turn are fossils of the magnetic field in star formation (Moss 1989). Assuming flux conservation, the surface fields observed in Ap/Bp stars ($\sim 10^2 - 2\times10^4$ G) are sufficient to explain the range of fields found in MWDs.

However, population synthesis suggest that only 40% of the known MWDs may have descended from Ap/Bp stars (Wickramasinghe & Ferrario 2005).

A clue to a possible link between binary evolution and strongly magnetic WDs came from the *absence* of detached MWD plus M-dwarf binaries, i.e. magnetic pre-CVs (Liebert et al. 2005b), which could not be explained within the Ap/Bp scenario. Differential rotation and convection are predicted to be key to a magnetic dynamo (Tout & Pringle 1992), both of which are prevalent in common envelope (CE) evolution. Tout et al. (2008) recently revisited the CE scenario for the formation of MWDs, and proposed that if a strong field is generated during a CE, the two possible outcomes are either a merger, leading to a single massive, strongly magnetic WD, or a short-period MWD plus low-mass star binary, that rapidly evolve into a mass-transferring CV state.

A key for testing which of the hypotheses is correct would be a set of wide common proper motion (CPM) MWDs. Here, we report the discovery of one such system. SDSS J130033.48+590407.0 (henceforth SDSS J1300+5904)

is a MWD and the CPM companion to the well-studied hydrogen-rich (DA) WD PG 1258+593. Following an estimate of the stellar parameters of SDSS J1300+5904, we discuss the evolutionary state of the CPM pair, and show that in this system, the Ap/Bp scenario provides a plausible explanation for the origin of the MWD. We also illustrate how WD CPM pairs may be used to constrain semi-empirical initial mass-final mass relations (IFMR) at the low-mass end.

2   OBSERVATIONS

One of the novelties within SDSS Data Release 7 (DR7) (Abazajian et al. 2009) are improvements in both the astrometric calibration, carried out against the UCAC2 catalogue (Zacharias et al. 2004), as well as an updated table of proper motions computed from the combined SDSS and USNO-B (Monet et al. 2003) positions. Using this proper motion table, we carried out a search for 3σ proper motion companions to WDs using the CasJobs SQL interface to SDSS DR7 (Li & Thakar 2008). One of the objects returned by our query was the faint blueish SDSS J1300+5904, which turned out to be a CPM companion to PG 1258+593[1]. The angular separation between the two objects is $16.1 \pm 0.1''$ (Fig. 1) and, at a distance of 68 ± 3 pc (see Sect. 3), the minimum binary separation is 1091 ± 7 AU. Coordinates, proper motions, and $ugriz$ point-spread function (PSF) magnitudes of both WDs are given in Table 1.

SDSS J1300+5904 had already been noted as a CPM companion by Farihi et al. (2005), however it was classified as a WD with a featureless (DC) spectrum, based on a relatively poor spectrum. Inspecting the SDSS fibre spectrum however unambiguously identifies it as a magnetic (DAH) WD given the clear detection of a Zeeman-triplet in Hα (Fig. 4). SDSS J1300+5904 was targeted for SDSS spectroscopy as a WD candidate; no SDSS spectrum was obtained for PG 1258+593.

We observed PG 1258+593 on February 13, 1997, using the Intermediate Dispersion Spectrograph (IDS) on the Isaac Newton Telescope (INT). Two spectra of 20 min exposure time each were obtained with the R632V grating and a $1.5''$ slit, covering the wavelength range 3680–5300 Å at a spectral resolution of ~ 2.3 Å. The data were reduced and calibrated as described by Moran et al. (1999), and the normalised line profiles are shown in Fig. 2.

3   WHITE DWARF PARAMETERS

We analysed the INT/IDS spectrum of PG 1258+593 using DA model spectra from Koester et al. (2005) and the fitting routine described by Rebassa-Mansergas et al. (2007). The best fit is achieved for $T_{\mathrm{eff}} = 14790 \pm 77$ K and log $g = 7.87 \pm 0.02$. Adopting these atmospheric parameters, we use an updated version of Bergeron et al.'s (1995) tables[2] to calculate the corresponding WD mass, 0.54 ± 0.01 M$_\odot$, radius, $(9.85 \pm 0.10) \times 10^8$ cm, and a cooling age of $(1.8 \pm$

---

[1] Initially identified as WD candidate GD 322 by Giclas et al. (1967)
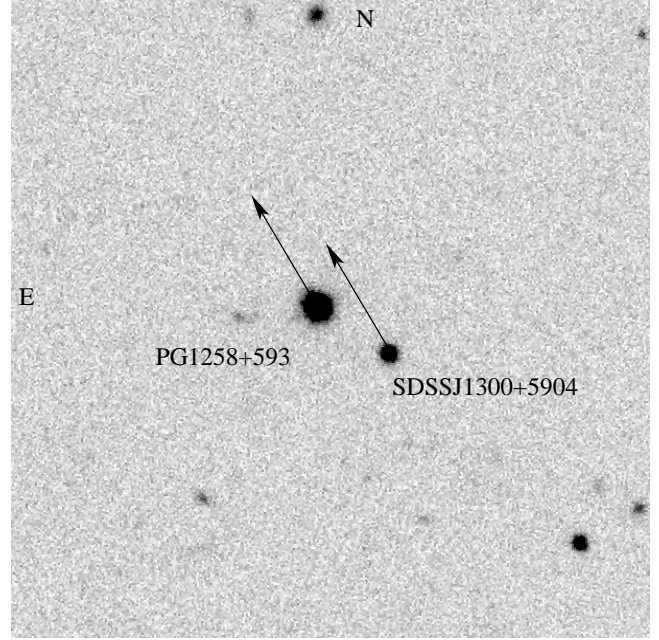[2] http://www.astro.umontreal.ca/~bergeron/CoolingModels/

Figure 1. $2' \times 2'$ r band SDSS image of the WD CPM pair. Proper motions are indicated over 300 years. An SDSS fibre spectrum was obtained for the fainter component of the binary.

$0.07) \times 10^8$ yr. Finally, we calculate $M_g = 11.03 \pm 0.1$, corresponding to a distance of 68 ± 3 pc (Table 2). The best fit is shown in Fig. 2. The $u - g$ vs $g - r$ colours of PG 1258+593 are broadly consistent with the results of the spectroscopic analysis (Fig. 3). Our atmospheric and stellar parameters for PG 1258+593 are in excellent agreement with those published by Liebert et al. (2005a) as part of their systematic analysis of the DA WDs from the Palomar Green Survey. They quote $T_{\mathrm{eff}} = 14480 \pm 229$ K, log $g = 7.87 \pm 0.05$, and $M_{\mathrm{wd}} = 0.54 \pm 0.02$ M$_\odot$.

Given the magnetic nature of SDSS J1300+5904, establishing its atmospheric parameters is not straight-forward, and we analysed the SDSS photometry and spectroscopy with both non-magnetic and magnetic model spectra.
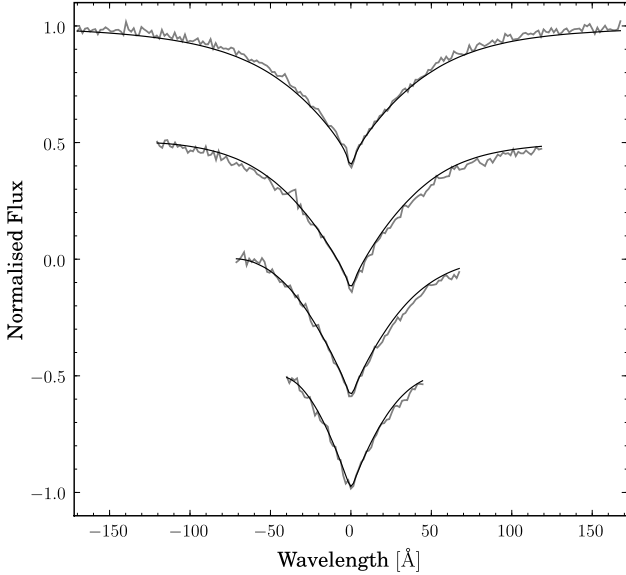
Figure 3 shows the location of SDSS J1300+5904 in the $u - g$ vs $g - r$ colour plane, which, while being somewhat displaced from the cooling tracks of non-magnetic DA WDs, clearly suggest a low temperature. As a first step, we performed a least χ^2 fit to the SDSS $ugriz$ magnitudes using model DA colours from Koester et al. (2005), which results in a temperature estimate of 6000 K. As expected from the morphology of the DA cooling tracks (Fig. 3), at such low temperatures, the colours provide very little information on log g. Taking the SDSS observations at face value, the u-band flux from the SDSS imaging appears somewhat too low compared to the flux level of the SDSS fibre spectrum (Fig. 4). Such offsets between the SDSS spectroscopy and photometry are found in a number of objects, and are in most cases strongest in the u-band. The discrepancy seen in SDSS J1300+5904 is consistent with the location of SDSS J1300+5904 in the $u - g$ vs $g - r$ colour plane (Fig. 3), where the $u - g$ colour of the object is too red with respect to the DA cooling tracks. A reduced u band flux with respect to the extrapolation of the spectrum could otherwise be caused by a large Balmer jump, contrary to that expected for a

Table 1. Coordinates, proper motions, and PSF magnitudes of the two WDs extracted from SDSS DR7.

Object	RA (2000)	Dec (2000)	p.m. [mas yr^{-1}] RA	Dec	u	g	r	i	z
PG 1258+593	13 00 35.20	+59 04 15.6	42.4 ± 2.6	75.0 ± 2.6	15.54 ± 0.01	15.20 ± 0.04	15.52 ± 0.02	15.76 ± 0.04	16.04 ± 0.02
SDSS J1300+5904	13 00 33.46	+59 04 06.9	41.8 ± 3.0	73.9 ± 3.0	19.08 ± 0.03	18.23 ± 0.04	17.93 ± 0.02	17.80 ± 0.04	17.79 ± 0.03

Figure 2. Normalised INT/IDS Hβ–Hϵ (top to bottom) line profiles of PG 1258+593 (gray line) and the best-fit model (black line) for $T_{\rm eff} = 14790$ K and $\log g = 7.87 \pm 0.02$.

Table 2. Atmospheric and stellar parameters for PG 1258+593 and SDSS J1300+5904.

	PG 1258+593	SDSS J1300+5904
$T_{\rm eff}$ [K]	14790 ± 77	6300 ± 300
$\log g$	7.87 ± 0.02	7.93 ± 0.11
$M_{\rm wd}$[M$_\odot$]	0.54 ± 0.01	0.54 ± 0.06
$R_{\rm wd}$[10^8 cm]	9.85 ± 0.10	9.33 ± 0.64
Cooling age [10^8 yr]	1.8 ± 0.07	18.5 ± 0.5
$B_{\rm wd}$[MG]	$\leqslant 0.3$	$\simeq 6$

per limits for $T_{\rm eff}$ between 6350 and 6650 K for a mass range from 0.47 to 0.63 M$_\odot$, which is consistent with the results we obtained from fitting the $griz$ magnitudes for the same distance.

We also fitted non-magnetic DA model spectra to the observed spectrum of SDSS J1300+5904. This results in $T_{\rm eff} \simeq 6500$ K, which corroborates the low temperature suggested by the photometry, but can obviously not properly account for the observed Balmer line profiles (Fig. 4).

Finally, fixing the distance to 68 ± 3 pc, and $\log g = 7.93$, we analysed the spectrum of SDSS J1300+5904 with magnetic WD models, using a simplified version of the code explained in Euchner et al. (2002) and following the procedure outlined in Külebi et al. (2009) to fit for a centred magnetic dipole. Due to the lack of a consistent theory that describes Stark broadening in the presence of magnetic fields in this regime (e.g. Jordan 1992) the computed line profiles are subject to systematic uncertainties. Hence discrepancies between the apparent strengths of the Balmer lines and the slope of the continuum are observed (see Achilleos et al. 1991). We have used the approach of Gänsicke et al. (2002) and used two different methods to asses the effective temperature: Fitting only the Balmer lines (6000 K) and fitting the continuum slope (6800 K). In the case where only Balmer lines are fitted the slope of the model spectrum is normalized with respect to the observed one. The Zeeman splitting observed in Hα implies a magnetic field strength of $\simeq 6$ MG and suggests an intermediate inclination between the line-of-sight and the magnetic axis. Figure 4 shows a magnetic model spectrum for a centered dipole with polar strength of 6 MG with an inclination of ~ 45 degrees as an example of a satisfying fit.

4 STELLAR EVOLUTION OF THE CPM PAIR

Within the errors, both WDs in this CPM pair have equal masses, similar or slightly below the mean mass of DA WDs, 0.593 ± 0.016M$_\odot$ (e.g. Koester et al. 1979; Finley et al. 1997; Liebert et al. 2005a; Kepler et al. 2007), but their different effective temperatures result in an age difference of $1.67 \pm$
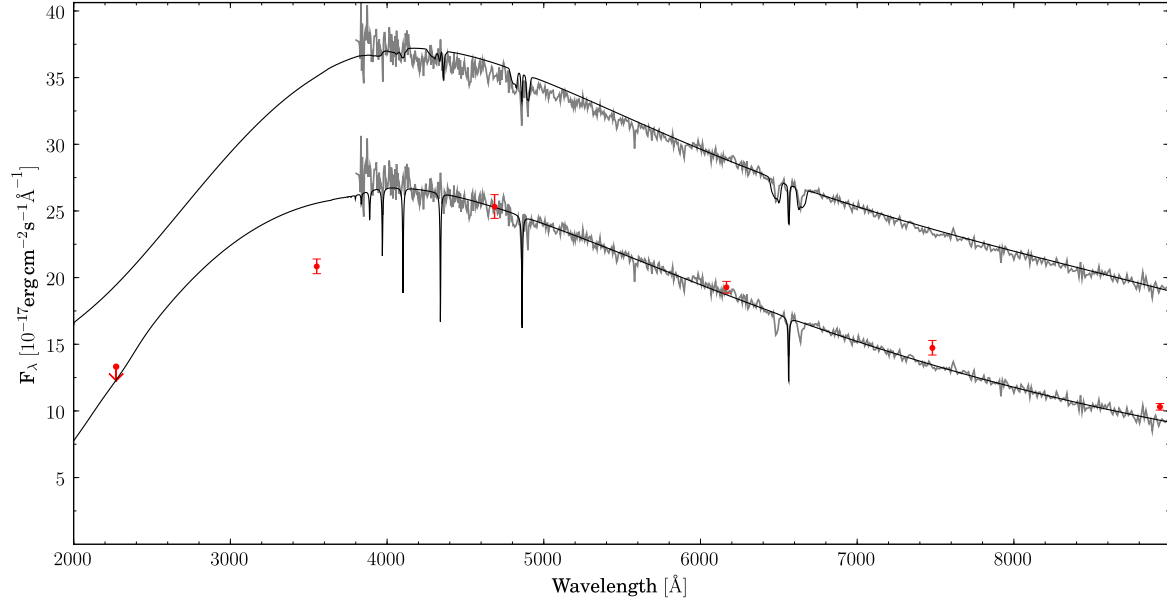
~ 6000 K DA WD. In reality, magnetic splitting probably leads to a shallower Balmer jump than in the non-magnetic case. Photometric variability due to rotation, such as observed e.g. in the magnetic WD GD 356 (Brinkworth et al. 2004), also cannot be ruled out, and further study is warranted.

In a second step, we made use of the known distance, $d = 68 \pm 3$ pc. For a given choice of $T_{\rm eff}$, we vary $\log g$ to match the observed SDSS magnitudes, and the best-fit $\log g$ then provides $M_{\rm wd}$ and $R_{\rm wd}$ by adopting a WD mass-radius relation (Wood 1995; Fontaine et al. 2001). In the light of the flux discrepancy in the u-band discussed above, we restrict the fit to the $griz$ magnitudes, and find $T_{\rm eff} = 6300 \pm 300$ K, $\log g = 7.93 \pm 0.13$, corresponding to a WD mass $M_{\rm wd} = 0.54 \pm 0.06$ M$_\odot$, radius $R_{\rm wd} = (9.33 \pm 0.64) \times 10^8$ cm, and cooling age of $1.7^{+0.4}_{-0.2} \times 10^9$ yr.

PG 1258+593 is detected by GALEX (Martin et al. 2005) at $m_{\rm fuv} = 15.30 \pm 0.02$ and $m_{\rm nuv} = 15.33 \pm 0.01$. Adopting $T_{\rm eff}$ and $\log g$ from Table 2, and $d = 68\pm3$ pc from above, we folded a DA model spectrum from (Koester et al. 2005) through the GALEX far and near-ultraviolet response curves, obtaining $m_{\rm fuv} = 15.37$ and $m_{\rm nuv} = 15.30$, in excellent agreement with the GALEX measurement when taking into account the low, but non-zero amount of reddening along the line of sight and the systematic uncertainties in the GALEX calibration. In contrast, SDSS J1300+5904 is not detected by GALEX. For an assumed distance of 68 pc, the limiting magnitude of GALEX, $m_{\rm nuv} = 20.5$, implies up-

Figure 4. The SDSS spectrum of SDSS J1300+5904 along with non-magnetic (bottom curves, $T_{\rm eff}$ = 6500 K, log g = 7.93) and magnetic (top curves, $T_{\rm eff}$ = 6000 K, log g = 7.93) WD models. The top curves are offset by 10 flux units. The magnetic WD model is calculated for a centered dipole with polar strength of 6 MG at an inclination against the line-of-sight of 45 degrees. Shown in red are the fluxes corresponding to the SDSS *ugriz* PSF magnitudes of SDSS J1300+5905. The left-most red point indicates the upper limit on the near-ultraviolet flux of SDSS J1300+5905 implied by the non-detection with GALEX.
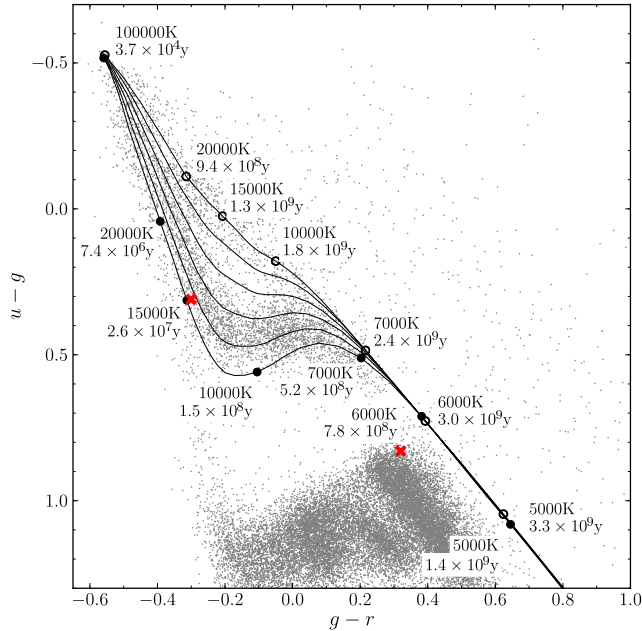

Figure 3. SDSS $u - g$ vs $g - r$ colour-colour diagram showing PG 1258+593 (left) and its magnetic CPM companion SDSS J1300+5904 (right) as red crosses. Theoretical DA cooling tracks shown as black lines for (from left to right) log $g = 7 - 9.5$ in steps of 0.5. The black open and black filled circles track log $g = 9.5$ and log $g = 7.0$ respectively, with corresponding cooling times.

0.05 Gyr, implying that their progenitor stars had rather different main-sequence life times.

It is long known that stars undergo different amounts of

mass loss depending on their initial mass, and Weidemann (1977) pioneered the investigation of the initial-final mass relation (IFMR) for WDs. The bulk of recent observational work constraining the IFMR has been carried out using WDs in open clusters spanning a range of ages (e.g. Ferrario et al. 2005; Kalirai et al. 2005; Dobbie et al. 2006; Catalán et al. 2008b,a; Kalirai et al. 2008; Rubin et al. 2008; Salaris et al. 2009; Casewell et al. 2009; Dobbie et al. 2009; Williams et al. 2009). These studies exploit the fact that the age of the cluster population can be determined from the main-sequence turn-off. The measured WD cooling age can then be used to calculate the lifetime of the WD progenitor and thus its initial mass can be estimated.

Clusters, however, are still relatively young, and therefore the low mass stars have not evolved into WDs yet. This means the low mass end of the IFMR, below $\sim 2\,{\rm M}_\odot$, is very poorly constrained, and the progenitors of both PG 1258+593 and SDSS J1300+5904 most likely had initial masses in this range. The question also remains as to whether the IFMR is indeed a one-valued relation, or whether there is a spread.

Wide WD binaries that did not interact during their evolution can in principle provide additional semi-empirical constraints on the IFMR. The cooling ages in such binaries can be determined from standard WD evolution models. The strongest constraints can be expected to come from binaries containing two WDs with unequal properties, such that the cooling ages differ significantly. This method has the advantage that some of the WDs will be of low mass and thus constrain the low mass end of the IFMR. To our knowledge, such an approach to the IFMR was attempted only twice. Greenstein et al. (1983) analysed the Sanduleak-Pesch WD binary (WD 1704+481), but their results were invalidated by the discovery that one of the two WDs is itself an unresolved

close WD binary that underwent a common-envelope evolution (Maxted et al. 2000). Finley & Koester (1997) modelled both components of PG 0922+162, a CPM binary containing two relatively massive WDs, and their results are consistent with the IFMR obtained from open clusters.

Here we make use of the age difference between PG 1258+593 and SDSS J1300+5904 to provide a semi-emirical upper limit on the progenitor mass of PG 1258+593. We adopt the main-sequence life times as a function of initial mass from the stellar evolution models of Pols et al. (1998). For any given choice of the progenitor mass of PG 1258+539 ($M_i^{\rm PG}$), the age difference of 1.67 ± 0.05 Gyr then implies a progenitor mass for SDSS J1300+5904 ($M_i^{\rm SDSS}$). Figure 5 illustrates the relation between $M_i^{\rm PG}$ and $M_i^{\rm SDSS}$ for solar and half-solar metalicity models with and without overshooting. As the main-sequence life time is a very strong function of the initial mass, $M_i^{\rm SDSS}$ levels off very steeply for $1.4 \lesssim M_i^{\rm PG} \lesssim 1.8$, and in a most conservative interpretation, $M_i^{\rm PG} < 2.2 \, {\rm M_\odot}$. Being more adventurous, one may choose to adopt the most recent IFMR cluster relations (e.g. Casewell et al. 2009; Salaris et al. 2009) to turn the mass of SDSS J1300+5904 into a conservative upper limit of $M_i^{\rm SDSS} < 3 \, {\rm M_\odot}$, and therefore $M_i^{\rm PG} < 1.8 \, {\rm M_\odot}$.

Admittedly, for a single WD binary this proves to be merely consistent with the current IFMR rather than improving it. It may however be in favour of a spread in the IFMR since we find two WDs with similar masses, yet very different ages and thus implying different progenitor masses. If we take current IFMRs, progenitor masses in the range $1-1.4 {\rm M_\odot}$ would be expected. The mass errors in Table 2 represent only the statistical uncertainty in fitting the observed Balmer lines with model spectra. Systematic uncertainties in the models and/or fitting procedure are difficult to assess, but are likely to outweigh the statistical errors. We estimate that the largest current mass difference consistent with the observational data is $\simeq 0.1 \, {\rm M_\odot}$, which would move, following the procedure outlined above, both progenitor stars into a range $\simeq 1 - 1.4 \, {\rm M_\odot}$.

Our study of PG 1258+593 and SDSS J1300+5904 outlines the potential of using WD CPM binaries for constraining the IFMR, bearing in mind that SDSS contains at least a few dozen of such binaries. However, to fully exploit this method, i.e. to reduce the spread seen in the relation shown in Fig 5, high-quality follow-up spectroscopy plus broadband photometry are necessary to deliver accurate $T_{\rm eff}$ and $\log g$ measurements.

A final caveat for the WD CPM binary presented in this study is that the magnetic field may have affected the IFMR for SDSS J1300+5904, however, there is currently no evidence for such an effect (Wickramasinghe & Ferrario 2005; Catalán et al. 2008b).

5 SDSS J1300+5905 AND THE ORIGIN OF MAGNETIC WHITE DWARFS

The origin of highly magnetic ($\gtrsim 1 \, {\rm MG}$) WDs is an unsettled issue. Early estimates of the fraction of MWDs hinted at a value of $\sim 4\%$ (e.g. Schmidt & Smith 1995), and led to the conclusion that their masses were on average higher than those of non-magnetic WDs (Liebert 1988). The space density of MWDs and their high masses were taken as
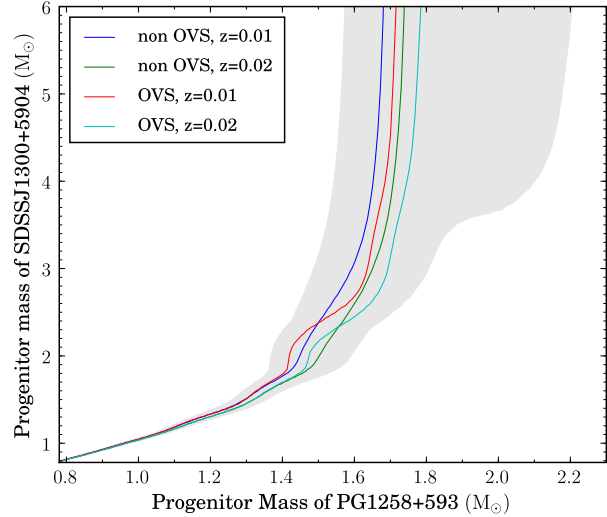

Figure 5. The mass of the progenitors star of SDSS J1300+5905 as a function of the mass of the progenitors star of PG 1258+593, given the difference between cooling ages indicate the difference between progenitor lifetimes. Calculations are made for over-shoot (OVS) and non over-shoot models, as well as solar ($z = 0.02$) and half solar ($z = 0.01$) metalicities. Allowing for 1σ errors on cooling times leads to a spread into the grey shaded region.

being suggestive for MWDs descending from chemical peculiar Ap/Bp stars, with the strong fields of the MWDs explained by magnetic flux conservation (e.g. Angel et al. 1981; Tout et al. 2004). However, more recent work suggests that the fraction of MWD may actually be as high as $10 - 15\%$ (Liebert et al. 2003; Wickramasinghe & Ferrario 2005), casting doubt as to whether the space density of Ap/Bp stars is sufficient for producing all MWDs (Kawka & Vennes 2004; Wickramasinghe & Ferrario 2005).

Liebert et al. (2005b) spotted another oddity about MWDs, namely that not a single MWD has been found in any of the > 1600 known (wide and close) WD plus M-dwarf binaries (Silvestri et al. 2007; Heller et al. 2009; Rebassa-Mansergas et al. 2009) – contrasting the large frequency of *interacting* MWD plus M-dwarf binaries, i.e. magnetic cataclysmic variables, which make up 25% of all known CVs (Wickramasinghe & Ferrario 2000). This motivated Tout et al. (2008) to outline a very different scenario for the origin of MWDs, in which dynamos during the common envelope evolution of close binaries generate strong magnetic fields in the core of the WD progenitor. During the common envelope of a WD plus M-dwarf binary, the separation shrinks, leading primarily to two different possible outcomes. If the two stars avoid merging, they leave the common envelope as a short-period binary that will relatively rapidly start mass transfer as a magnetic cataclysmic variable. In fact, a number of such systems, magnetic pre-cataclysmic variables, are known (Reimers et al. 1999; Reimers & Hagen 2000; Szkody et al. 2003; Schmidt et al. 2007; Schwope et al. 2009). Alternatively, the two stars may coalesce, forming a single MWD, which will typically be more massive than non-magnetic field WDs.

Given the larger number of observational constraints that are available for MWDs in binaries, these systems hold

Table 3. Known spatially resolved double degenerate systems with one magnetic component.

Name	MWD			Companion			separation		Ref.
	T_{eff} [K]	$M_{\mathrm{wd}}[\mathrm{M_\odot}]$	B [MG]	Type	T_{eff} [K]	M_{wd} [$\mathrm{M_\odot}$]	['']	AU	
LB 11146	16000	0.9	670	DA	14500	0.91 ± 0.07	0.015	~ 0.6	1,2,3,4
RE J0317-853	33800	1.32	340	DA	16000	~ 0.93	6.7	~ 200	5,6,7,8
SDSS J130033.48+590407.0	6300 ± 300	0.54 ± 0.06	$\simeq 6$	DA	14790 ± 77	0.54 ± 0.01	16.1 ± 0.1	$\gtrsim 1091$	9

[1] Liebert et al. (1993); [2] Glenn et al. (1994); [3] Schmidt et al. (1998); [4] Nelan (2007); [5] Barstow et al. (1995); [6] Ferrario et al. (1997); [7] Burleigh et al. (1999); [8] Vennes et al. (2003); [9] this paper.

a strong potential in improving our understanding of the origin of MWDs. Until now, only two spatially resolved WD binaries containing one MWD were known, RE J0317–853 and LB 11146, see Table 3. RE J0317–853 is hot, massive WD, rotating with a spin period of 725 sec, and has a very large magnetic field (Barstow et al. 1995; Burleigh et al. 1999). Its DA companion LB 9802 is cooler and of lower mass[3] than RE J0317–853, a paradox in terms of stellar evolution which is resolved if the magnetic component is assumed to be a relatively recent merger (Ferrario et al. 1997). LB 11146 is a relatively close binary, that might have undergone a common envelope evolution (Nelan 2007). Hence, the properties of both RE J0317–853 and LB 11146 are consistent with a binary origin of the magnetic field. In addition to these two spatially resolved WD plus MWD binaries, about half a dozen unresolved spectroscopic WD binaries containing an MWD are known (Kawka et al. 2007, and references therein), and hence it is not known if they underwent binary interaction or not.

PG 1258+593/SDSS J1300+5904 differ from the two previously known spatially resolved binaries in that the two WDs appear to have evolved without interacting, and their properties agree with standard stellar evolution theory. Taken the observational facts at face value, it seems entirely plausible that the strong magnetic field of SDSS J1300+5904 is related to the Ap phenomenon and not related to a common envelope evolution, unless it is itself an unresolved binary, or unrecognised merger. The first option appears contrived, but not impossible (see the case of WD 1704+481; Maxted et al. 2000). The SDSS spectrum shows no evidence for an additional binary companion, unless it is a featureless DC WD, similar to that in G62-46 (Bergeron et al. 1993), or a very late type dwarf. Using the star spectral templates of Araujo-Betancor et al. (2005), a hypothetical unresolved late type companion to SDSS J1300+5904 has to be of spectral type L5 or later to go unnoticed. WD plus brown dwarf binaries are extremely rare (Farihi et al. 2005), so finding one with a CPM WD companion appears rather unlikely, however infrared data could rule this out for certain. The second option, a merger, can also not be excluded. The mass of SDSS J1300+5904 is slightly below the mean mass for single WDs, so any merger event would have either been the merger of two low mass WDs, possibly helium core WDs, or had to involve a low mass star. In the

case that SDSS J1300+5904 is the product of a merger, one would expect the WD to be rapidly spinning, which might be detected via photometric variability (e.g. Brinkworth et al. 2004, 2005). Thus SDSS J1300+5904 warrants further study.

6   CONCLUSIONS

We have shown how wide, non-interacting WD pairs can be used to constrain the IFMR. We have also shown that SDSS J1300+5904, the CPM companion to the DA WD PG 1258+593, is a MWD with $B \simeq 6$ MG. The masses of both WDs are $\sim 0.54\,\mathrm{M_\odot}$, slightly below the average of non-magnetic WDs. Nevertheless, the two WDs exhibit a significant difference in their effective temperatures, implying an age difference of ~ 1.6 Gyr. Adopting standard stellar evolution models, we show that assuming a progenitor mass of $\sim 1.5\,\mathrm{M_\odot}$ for PG 1258+593 implies a progenitor mass of $\sim 2 - 3\,\mathrm{M_\odot}$ for SDSS J1300+5904, consistent with the mass of Ap stars. An origin of the magnetic field related to common envelope evolution is not impossible, but requires the assumption of an initial triple system.

REFERENCES

Abazajian, K. N., et al., 2009, ApJS, 182, 543
Achilleos, N., Remillard, R. A., Wickramasinghe, D. T., 1991, MNRAS, 253, 522
Angel, J. R. P., Borra, E. F., Landstreet, J. D., 1981, ApJS, 45, 457
Araujo-Betancor, S., et al., 2005, A&A, 430, 629
Barstow, M. A., Jordan, S., O'Donoghue, D., Burleigh, M. R., Napiwotzki, R., Harrop-Allin, M. K., 1995, MNRAS, 277, 971
Bergeron, P., Ruiz, M.-T., Leggett, S. K., 1993, ApJ, 407, 733
Bergeron, P., Wesemael, F., Beauchamp, A., 1995, PASP, 107, 1047
Brinkworth, C. S., Burleigh, M. R., Wynn, G. A., Marsh, T. R., 2004, MNRAS, 348, L33
Brinkworth, C. S., Marsh, T. R., Morales-Rueda, L., Maxted, P. F. L., Burleigh, M. R., Good, S. A., 2005, MNRAS, 357, 333

[3] The physical association of RE J0317–853 is so far purely based on the small separation on the sky, no proper motions are available for the two stars. However, a preliminary analysis of HST/FGS data does appear compatible with the system being a CPM pair (Jordan et al. in prep.).

Burleigh, M. R., Jordan, S., Schweizer, W., 1999, ApJ Lett., 510, L37

Casewell, S. L., Dobbie, P. D., Napiwotzki, R., Burleigh, M. R., Barstow, M. A., Jameson, R. F., 2009, MNRAS, 395, 1795

Catalán, S., Isern, J., García-Berro, E., Ribas, I., 2008a, MNRAS, 387, 1693

Catalán, S., Isern, J., García-Berro, E., Ribas, I., Allende Prieto, C., Bonanos, A. Z., 2008b, A&A, 477, 213

Dobbie, P. D., Napiwotzki, R., Burleigh, M. R., Williams, K. A., Sharp, R., Barstow, M. A., Casewell, S. L., Hubeny, I., 2009, MNRAS, 395, 2248

Dobbie, P. D., et al., 2006, MNRAS, 369, 383

Euchner, F., Jordan, S., Beuermann, K., Gänsicke, B. T., Hessman, F. V., 2002, A&A, 390, 633

Farihi, J., Becklin, E. E., Zuckerman, B., 2005, ApJS, 161, 394

Ferrario, L., Vennes, S., Wickramasinghe, D. T., Bailey, J. A., Christian, D. J., 1997, MNRAS, 292, 205

Ferrario, L., Wickramasinghe, D., Liebert, J., Williams, K. A., 2005, MNRAS, 361, 1131

Finley, D. S., Koester, D., 1997, ApJ Lett., 489, L79

Finley, D. S., Koester, D., Basri, G., 1997, ApJ, 488, 375

Fontaine, G., Brassard, P., Bergeron, P., 2001, PASP, 113, 409

Gänsicke, B. T., Euchner, F., Jordan, S., 2002, A&A, 394, 957

Giclas, H. L., Burnham, R., Thomas, N. G., 1967, Lowell Observatory Bulletin, 7, 49

Glenn, J., Liebert, J., Schmidt, G. D., 1994, PASP, 106, 722

Greenstein, J. L., Dolez, N., Vauclair, G., 1983, A&A, 127, 25

Heller, R., Homeier, D., Dreizler, S., Østensen, R., 2009, A&A, 496, 191

Jordan, S., 1992, A&A, 265, 570

Kalirai, J. S., Richer, H. B., Reitzel, D., Hansen, B. M. S., Rich, R. M., Fahlman, G. G., Gibson, B. K., von Hippel, T., 2005, ApJ Lett., 618, L123

Kalirai, J. S., Hansen, B. M. S., Kelson, D. D., Reitzel, D. B., Rich, R. M., Richer, H. B., 2008, ApJ, 676, 594

Kawka, A., Vennes, S., 2004, in Zverko, J., Ziznovsky, J., Adelman, S. J., Weiss, W. W., eds., The A-Star Puzzle, vol. 224 of *IAU Symposium*, p. 879

Kawka, A., Vennes, S., Schmidt, G. D., Wickramasinghe, D. T., Koch, R., 2007, ApJ, 654, 499

Kepler, S. O., Kleinman, S. J., Nitta, A., Koester, D., Castanheira, B. G., Giovannini, O., Costa, A. F. M., Althaus, L., 2007, MNRAS, 375, 1315

Koester, D., Schulz, H., Weidemann, V., 1979, A&A, 76, 262

Koester, D., Napiwotzki, R., Voss, B., Homeier, D., Reimers, D., 2005, A&A, 439, 317

Külebi, B., Jordan, S., Euchner, F., Gänsicke, B. T., Hirsh, H., 2009, A&A, in press, arXiv:0907.2372

Li, N., Thakar, A. R., 2008, Computing in Science and Engineering, 10, 18

Liebert, J., 1988, PASP, 100, 1302

Liebert, J., Bergeron, P., Schmidt, G. D., Saffer, R. A., 1993, ApJ, 418, 426

Liebert, J., Bergeron, P., Holberg, J. B., 2003, AJ, 125, 348

Liebert, J., Bergeron, P., Holberg, J. B., 2005a, ApJS, 156, 47

Liebert, J., et al., 2005b, AJ, 129, 2376

Martin, D. C., et al., 2005, ApJ Lett., 619, L1

Maxted, P. F. L., Marsh, T. R., Moran, C. K. J., Han, Z., 2000, MNRAS, 314, 334

Monet, D. G., et al., 2003, AJ, 125, 984

Moran, C., Maxted, P., Marsh, T. R., Saffer, R. A., Livio, M., 1999, MNRAS, 304, 535

Moss, D., 1989, MNRAS, 236, 629

Nelan, E. P., 2007, AJ, 134, 1934

Pols, O. R., Schroder, K.-P., Hurley, J. R., Tout, C. A., Eggleton, P. P., 1998, MNRAS, 298, 525

Rebassa-Mansergas, A., Gänsicke, B. T., Rodríguez-Gil, P., Schreiber, M. R., Koester, D., 2007, MNRAS, 382, 1377

Rebassa-Mansergas, A., Gänsicke, B., Schreiber, M., Koester, D., Rodríguez-Gil, P., 2009, MNRAS, submitted

Reimers, D., Hagen, H. J., 2000, A&A, 358, L45

Reimers, D., Hagen, H. J., Hopp, U., 1999, A&A, 343, 157

Rubin, K. H. R., Williams, K. A., Bolte, M., Koester, D., 2008, AJ, 135, 2163

Salaris, M., Serenelli, A., Weiss, A., Miller Bertolami, M., 2009, ApJ, 692, 1013

Schmidt, G. D., Smith, P. S., 1995, ApJ, 448, 305

Schmidt, G. D., Liebert, J., Smith, P. S., 1998, AJ, 116, 451

Schmidt, G. D., Szkody, P., Henden, A., Anderson, S. F., Lamb, D. Q., Margon, B., Schneider, D. P., 2007, ApJ, 654, 521

Schmidt, G. D., et al., 2003, ApJ, 595, 1101

Schwope, A. D., Nebot Gomez-Moran, A., Schreiber, M. R., Gänsicke, B. T., 2009, A&A, 500, 867

Silvestri, N. M., et al., 2007, AJ, 134, 741

Szkody, P., et al., 2003, ApJ, 583, 902

Tout, C. A., Pringle, J. E., 1992, MNRAS, 259, 604

Tout, C. A., Wickramasinghe, D. T., Ferrario, L., 2004, MNRAS, 355, L13

Tout, C. A., Wickramasinghe, D. T., Liebert, J., Ferrario, L., Pringle, J. E., 2008, MNRAS, 387, 897

Vanlandingham, K. M., et al., 2005, AJ, 130, 734

Vennes, S., Schmidt, G. D., Ferrario, L., Christian, D. J., Wickramasinghe, D. T., Kawka, A., 2003, ApJ, 593, 1040

Weidemann, V., 1977, A&A, 59, 411

Wickramasinghe, D. T., Ferrario, L., 2000, PASP, 112, 873

Wickramasinghe, D. T., Ferrario, L., 2005, MNRAS, 356, 1576

Williams, K. A., Bolte, M., Koester, D., 2009, ApJ, 693, 355

Wood, M. A., 1995, in Koester, D., Werner, K., eds., White Dwarfs, no. 443 in LNP, Springer, Heidelberg, p. 41

York, D. G., et al., 2000, AJ, 120, 1579

Zacharias, N., Urban, S. E., Zacharias, M. I., Wycoff, G. L., Hall, D. M., Monet, D. G., Rafferty, T. J., 2004, AJ, 127, 3043

This paper has been typeset from a T$_{\rm E}$X/ L$^{\rm A}$T$_{\rm E}$X file prepared by the author.